APPARATUS AND METHOD FOR ISOLATING AND MEASURING MOVEMENT IN A METROLOGY APPARATUS

BACKGROUND OF THE INVENTION

Cross-Reference to Related Applications

This application is a continuation application of U.S. Serial No. 09/855,960, filed May 15, 2001, now U.S. Patent No. 6,530,268, which is a continuation application of U.S. Serial No. 09/803,268, filed March 9, 2001, each of which is expressly incorporated by reference herein in its entirety.

Field of the Invention

This invention relates to scanning probe microscopes (SPMs) and other related metrology apparatus. More particularly, it is directed to an apparatus and method for measuring the movement of a sample to be analyzed by an SPM, and to isolate its Z movement from parasitic X-Y movement generated by a Z actuator.

Discussion of the Prior Art

Scanning probe microscopes are typically used to determine the surface characteristics of a sample, commonly biological or semiconductor samples, to a high degree of accuracy, down to the Ångstrom scale. Two common forms of the scanning probe microscope are shown in FIGURES 1A and 1B. A scanning probe microscope operates by providing relative scanning movement between a measuring probe assembly having a sharp stylus and a sample surface while measuring one or more properties of the surface. The examples shown in FIGURES 1A and 1B are atomic force microscopes ("AFMs") where a measuring probe assembly 12 includes a sharp tip or stylus 14 attached to a flexible cantilever 16. Commonly, an actuator such as a piezoelectric tube (often referred to herein as a "piezo tube") is used to generate relative motion between the measuring probe 12 and the

sample surface. A piezoelectric tube is a device that moves in one or more directions when voltages are applied to electrodes disposed inside and outside the tube (29 in FIGURE 1C).

In FIGURE 1A, measuring probe assembly 12 is attached to a piezoelectric tube actuator 18 so that the probe may be scanned over a sample 20 fixed to a support 22. FIGURE 1B shows an alternative embodiment where the probe assembly 12 is held in place and the sample 20, which is coupled to a piezoelectric tube actuator 24, is scanned under it. In both AFM examples in FIGURES 1A and 1B, the deflection of the cantilever 16 is measured by reflecting a laser beam 26 off the back side 27 of cantilever 16 and towards a position sensitive detector 28.

One of the continuing concerns with these devices is how to improve their accuracy. Since these microscopes often measure surface characteristics on the order of Ångstroms, positioning the sample and probe with respect to each other is critical. Referring to FIGURE 1C, as implemented in the arrangement of FIGURE 1A, when an appropriate voltage (V_x or V_y) is applied to electrodes 29 disposed on the upper portion 30 of piezoelectric tube actuator 18, called an X and Y axis translating section or more commonly an "X-Y tube," the upper portion may bend in two axes, the X and Y axes as shown. When a voltage (V_z) is applied across electrodes 29 in the lower portion 32 of tube 18, called a Z axis translating section or more commonly a "Z-tube," the lower portion extends or retracts, generally vertically. In this manner, portions 30, 32 and the probe (or sample) can be steered left or right, forward or backward and up and down. This arrangement provides three degrees of freedom of motion. For the arrangement illustrated in FIGURE 1A, with one end fixed to a microscope frame (for example, 34 in FIGURE 1D), the free end of tube 18 can be moved in three orthogonal directions with relation to the sample 20. In addition, with the X-Y tube 30 on top of the Z-tube 32 (i.e., furtherest from probe assembly 12), maximum X-Y range is realized.

Unfortunately, piezoelectric tubes and other types of actuators are imperfect. For example, the piezo tube often does not move only in the intended direction. FIGURE 1D shows an undesirable, yet common, case where a piezo tube actuator 18 was commanded to

move in the Z-direction (by the application of an appropriate voltage between the inner and outer electrodes, 29 in FIGURE 1C), but where, in response, the Z tube 18 moves not only in the Z direction, but in the X and/or Y directions as well. This unwanted parasitic motion, shown in FIGURE 1D as ΔX (not to scale), limits the accuracy of measurements obtained by scanning probe microscopes. Similar parasitic motion in the Y direction is also common. The amount of this parasitic motion varies with the geometry of the tube and with the uniformity of the tube material, but typically cannot be eliminated to the accuracy required by present instruments.

Current methods of monitoring the motion of the probe or sample 20 when driven by a piezoelectric tube in either the arrangement of FIGURE 1A or FIGURE 1B are not sufficiently developed to compensate for this parasitic X and Y error. The devices are typically calibrated by applying a voltage to the X-Y tube and the Z tube, and then measuring the actual distance that the sample or probe travels. Thus, the position of the piezo tube is estimated by the voltage that is applied to the X-Y tube and the Z tube. However, because the (X,Y) position error introduced by the Z tube on the probe (or on the sample for the arrangement shown in FIGURE 1B) is essentially random, it cannot be eliminated merely by measuring the voltage applied to the Z tube or to the X-Y tube.

Moreover, with respect to movement in the intended direction, piezoelectric tubes and other types of actuators typically do not move in a predictable way when known voltages are applied. The ideal behavior would be that the actuator move in exact proportion to the voltage applied. Instead actuators, including piezo tubes, move in a non-linear manner, meaning that their sensitivity (e.g., nanometers of motion per applied voltage) can vary as the voltage increases. In addition, they suffer from hysteresis effects. Most generally, the response to an incremental voltage change will depend on the history of previous voltages applied to the actuator. This hysteresis effect, thus, can cause a large prior motion to affect the response of a commanded move, even many minutes later.

Additionally, vertical measurements in scanning probe microscopy are typically calculated mathematically by recording the voltage applied to the piezoelectric tube and then multiplying by the tube's calibrated sensitivity in nm/V. But as mentioned previously, this sensitivity is not constant and depends on the previous voltages applied to the tube. So using the voltage applied to the tube to calculate the vertical motion of the tube will always result in an error with respect to the actual motion. This error can translate directly into errors when measuring surface topography of a sample and performing other metrology experiments. These issues have been addressed specifically for the case in which the probe assembly of the AFM is coupled to the actuator (i.e., the case in which the probe assembly moves in three orthogonal directions, for example, in the cases cross-referenced above).

What is needed, therefore, is an apparatus and method for accurately measuring and controlling the motion of the sample or probe by minimizing adverse parasitic motion introduced by an actuator (e.g., a Z tube) in a metrology apparatus where the sample is scanned. In particular, if the adverse parasitic motion is minimized, the intended motion of the sample or probe will be realized and the apparatus will accurately measure and track the actual motion of the sample or probe in the X and/or Y directions in response to voltages applied to an XY actuator.

SUMMARY OF THE INVENTION

The present invention is directed to an apparatus and method for isolating vertical or Z-motion of a SPM actuator and measuring the motion of a sample coupled to the actuator in a direction generally perpendicular to a longitudinal axis of an elongate actuator (e.g., movement in the XY plane). The apparatus implements an optical detection apparatus including an objective (e.g., a set of microlenses) mounted to a reference structure coupled to the actuator, wherein the reference structure minimizes negative effects associated with parasitic motion introduced, for example, by the actuator (e.g., a Z tube) in a metrology apparatus such as an AFM or a profiler. A light beam is generated by a light source and directed through the objective and towards a position sensor that detects changes in the direction of the beam indicative of actual movement of a sample in response to voltage

signals applied to an XY actuator. This rigid mechanical structure that includes a fixed probe that scans a sample by translating the sample via the actuator to which it is mounted results in higher resolution than a moving probe scanning a fixed sample and thus is particularly adapted for research applications.

According to a first aspect of the preferred embodiment, an assembly for a metrology apparatus includes an actuator with a longitudinal axis having a fixed end and a free end configured to be translated in, preferably, three orthogonal directions with respect to the fixed end. A multiple bar linkage having first and second links mutually constrained to translate with respect to each other, the first link being fixed to a reference structure and the second link being constrained to translate in a direction generally parallel to the longitudinal axis of the actuator. A sample holder is supported by a multiple bar linkage. A coupling has first and second opposed ends with the first end fixed to the actuator proximate its free end, and the second end fixed to the second link. The coupling is adapted to transmit displacement in a direction substantially parallel to the longitudinal axis of the actuator.

According to another aspect of this embodiment, the actuator has a z-axis translating section and an x and y-axis translating section which is disposed between the fixed end of the apparatus and the z-axis translating section. The reference structure is mechanically independent from translation of the z-axis translating section but is mechanically responsive to the x and y-axis translating section.

According to yet another aspect of this embodiment, the reference structure is fixed to the multiple bar linkage to deflect the multiple bar linkage in the X and Y directions in response to X and Y deflections of the x and y-axis translating stage. The multi-bar linkage further includes a first mirror fixed to a least one of the links of the multi-bar linkage, and a second mirror fixed to another of the links of the multi-bar linkage.

In another aspect of the preferred embodiment, an assembly for a metrology apparatus has a probe assembly that includes an elongate actuator with a longitudinal axis,

the actuator having a first end configured to be coupled to a frame of the microscope and a free end configured to be coupled to a sample holder. The elongate actuator provides controllable translation in, preferably, three orthogonal directions upon application of proper electrical stimuli.

A method of reducing positioning errors at the free end of the elongate actuator includes the steps of fixing the probe assembly to the frame, and supporting the sample holder with a reference structure of the metrology apparatus, the reference structure being substantially insensitive to longitudinal expansion or contraction of the elongate actuator. The method also includes isolating the reference structure from a longitudinal tube deflection of the elongate actuator and driving a first portion of the elongate actuator so as to simultaneously generate both longitudinal deflections and lateral deflections in the first portion. In this method, the system prevents the lateral deflections generated in the longitudinally expanding and contracting portion of the tube from laterally deflecting the sample holder while simultaneously transmitting the longitudinal deflections to the sample holder.

In another aspect of this preferred embodiment, a second portion of the elongate actuator is configured to provide translation in a plane substantially perpendicular to the longitudinal direction. As such, the method includes driving the second portion of the elongate actuator and generating lateral deflections in the second portion as a result of the driving of the second portion step. Moreover, the method includes transmitting the lateral deflections in the second portion to the sample holder.

Another preferred embodiment of the present invention is directed to a scanning probe microscope assembly including a microscope frame and a piezoelectric actuator having a first end fixed to the frame and a second free end supporting a sample. A first reflector assembly is fixed proximate to the free end of the piezoelectric actuator. A first electromagnetic radiation source fixed with respect to the frame is disposed to direct radiation onto the first reflector assembly. The first electromagnetic radiation detector is

disposed to receive light from the first source after it has been received and reflected by the first reflector assembly and to generate a signal indicative of a degree of longitudinal deflection of the piezoelectric actuator.

According to a still further aspect of the preferred embodiment, an optical apparatus for measuring movement of an actuator in a metrology apparatus includes a sample holder coupled to the actuator, an optical measuring device including a light source that generates a light beam, the device being configured to change the direction of the beam in response to movement of the actuator. The system also includes a sensor to detect the beam and generate a signal indicative of the movement of the actuator.

According to yet another aspect of the preferred embodiment of the present invention, a method for measuring movement of an actuator in a metrology apparatus includes providing a movable bar assembly coupled to the actuator and to a reference structure, and supporting a sample holder with the movable bar assembly. The method measures movement of the movable bar assembly in operation.

In another aspect of the preferred embodiment, a reference assembly is employed to generally decouple movement of the apparatus, in a direction other than the intended direction, from the sample. The reference assembly includes a reference structure and a sample holder coupled to the reference structure and to the actuator. The sample is attached to the sample holder. A flexible bar having opposed ends, a first of which is coupled to the actuator and the other of which is coupled to the sample holder. The flexible bar, reference structure and flexure are adapted to collectively decouple movement of the microscope, in the direction other than the intended direction, from the probe.

According to a further aspect of the preferred embodiment, a metrology apparatus for analyzing a sample includes an actuator which includes a first actuator stage configured to controllably move in first and second orthogonal directions. A second actuator stage preferably is disposed adjacent to the first actuator stage and is configured to controllably

move in a third direction orthogonal to the first and second orthogonal directions. A reference structure having first and second ends is fixed relative to movement of the second actuator stage. A coupling coupled to the second actuator stage and to a multi-bar linkage assembly is fixed to the second end of the reference structure. The second actuator stage and the coupling are configured to move the linkage in the third orthogonal direction in a manner that substantially isolates the linkage from any second actuator stage motion in the first and second directions. An objective fixed to the second end of the reference structure is between a light source and a position sensor. The position sensor measures the first actuator stage motion in the first and second directions. In this embodiment, the multi-bar linkage supports the sample.

These and other objects, features, and advantages of the invention will become apparent to those skilled in the art from the following detailed description and the accompanying drawings. It should be understood, however, that the detailed description and specific examples, while indicating preferred embodiments of the present invention, are given by way of illustration and not of limitation. Many changes and modifications may be made within the scope of the present invention without departing from the spirit thereof, and the invention includes all such modifications.

BRIEF DESCRIPTION OF THE DRAWINGS

A preferred exemplary embodiment of the invention is illustrated in the accompanying drawings in which like reference numerals represent like parts throughout, and in which:

FIGURE 1A is a partial side elevational view of a prior art atomic force microscope utilizing a scanned stylus and including a three-axis piezoelectric actuator assembly;

FIGURE 1B is a partial side elevational view of a prior art atomic force microscope utilizing a scanned sample and including a three-axis piezoelectric actuator assembly;

FIGURE 1C is a perspective view of a prior art piezoelectric tube actuator of an atomic force microscope;

FIGURE 1D is a front elevational view illustrating parasitic motion of a piezoelectric actuator assembly configured to move in a predetermined direction, in this case "Z";

FIGURE 2 is a perspective assembly view of a scanning probe microscope and apparatus for measuring motion in the Z direction according to the preferred embodiment;

FIGURE 3 is a front cross-sectional view of the scanning probe microscope of FIGURE 2;

FIGURE 4 is a partial broken away cross-sectional view of the scanning probe microscope shown in FIGURE 2; and

FIGURE 5 is a side elevational view of a scanning probe microscope assembly according to the present invention; and

FIGURE 6 is a side cross-sectional view of a scanning probe microscope assembly of FIGURE 5.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring initially to FIGURE 2, a scanning probe microscope (SPM) 100 is shown. The microscope includes a chassis including a support 102 to which a probe assembly 104 is attached. Probe assembly 104 is configured to interact with a sample 106. More particularly, probe assembly 102 is kept stationary while sample 106 is translated, preferably in raster scan fashion, relative thereto to image or otherwise collect data pertaining to the sample. An actuator assembly 108 includes an actuator 110 for translating the sample 106, and a reference assembly 112 defining, among other structure, an elongate reference structure 114 that surrounds actuator 110. Reference structure 114 is tubular and has a longitudinal axis that is generally collinear with the longitudinal axis of actuator 110. Actuator 110 is preferably piezoelectric or electrostrictive, and may be a tube actuator or another type of actuator conventional in the art of nanopositioning systems. Actuator 110 is fixed to a mount 116 which is also coupled to the chassis of the microscope.

Probe assembly 104 is fixed to support 102 and includes a cantilever 118 having a stylus (i.e., tip) 120 either attached thereto or formed integrally therewith. During operation, the surface of sample 106 is scanned beneath fixed stylus 120 to determine characteristics

(for example, surface topography) of sample 106. The scanning operation is provided by actuator 110, which is driven by program-controlled signals (e.g., appropriate voltages) to cause the actuator 110 to move laterally in two dimensions, as well as to extend and retract in this embodiment. This movement of the actuator is transmitted to sample 106 which is mounted on a sample mount 122 that translates in conjunction with actuator 110. For example, actuator 110 can move sample 106 toward or away from tip 120 in a vertical direction in response to closed loop signals derived from a sensor 121 (as shown in figure 4), in conventional fashion as described below.

In this regard, referring to Figures 2, 3 and 4, an electro-magnetic radiation source 119 (e.g., a laser) is fixed to support 102. In operation, source 119 directs light towards a backside of cantilever 118 of probe assembly 104. Detector 121 receives the light reflected from the probe, and in turn, generates a corresponding signal. In this fashion, deflection of cantilever 118 as tip 120 interacts with the scanning sample surface 106 can be monitored. Again, the signals generated by the deflection of cantilever are used in a closed loop feedback configuration to control actuator 110, and more particularly, to control the separation between tip 120 and sample surface 106, thus providing information about the sample surface. Note that we refer hereinafter to the extending and retracting of sample 106 toward and away from tip 120 as motion in the Z direction, and translation of sample 106 laterally relative to tip 120 as motion in the X direction and the Y direction, where the X and the Y axes are orthogonal to each other and define a plane substantially parallel to the surface of sample 106. This nomenclature is used purely for convenience to indicate three orthogonal directions.

As noted, actuator 110 preferably translates sample 106 in three orthogonal directions under program control. This is preferably implemented as shown in the Figures where actuator 110 includes an X-Y tube section 126 coupled to the chassis and a Z tube section 124 coupled to X-Y tube 126. Z tube section 124 has a free end coupled to sample 106, preferably positioned on top of X-Y tube 126 to maximize the range of X-Y motion provided by X-Y tube 126.

Minimizing The Effect Of Parasitic Movement Of The Sample

Next, to illustrate one aspect of the preferred embodiment, we turn to FIGURES 2-4 which show an apparatus for ensuring that displacements generated by actuator 110 and transferred to the scanned sample 106 coupled thereto are isolated from movement of actuator 110 in a direction other than the intended direction of the actuator; in other words, the preferred embodiment operates so that intended displacements of the actuator are, in the best case, completely isolated from parasitic movement of actuator 110. In this regard, actuator 110 is coupled to a movement isolating device 132 such as a flexure via a flexible bar or element 134 (i.e., a coupling) that is adapted to transmit displacement only in an intended direction. As a result, adverse effects associated with non-intended movement of the metrology apparatus 100, such as parasitic movement of actuator 110 are minimized, as described in further detail below.

In FIGURES 2 and 3, for example, a mount 135 attached to Z tube section 124 of actuator 110 is coupled to flexure 132 with flexible bar coupling 134. In this case, coupling 134 is configured so as to transmit displacement generated by actuator 110 (and particularly Z tube 124 of actuator 110) in the Z or vertical direction, but generally not displacement of Z tube 124 in the X and Y directions.

To realize this minimization of parasitic movement of actuator 110, flexure 132 is also coupled to fixed reference structure 114. Flexure 132 is preferably a parallelogram flexure comprising a four-bar linkage that is adapted to translate so that its opposed vertical links 150, 152 remain generally orthogonal to the X-Y plane in response to a force, and therefore displacement, transmitted in the vertical or Z direction by bar 134. This movement of flexure 132 is rotational about points 158, 160, 162, 164 thereof.

To ensure that the opposed vertical links of flexure 132 move in this fashion, flexible element 134 is configured so as to be sufficiently rigid to transmit vertical displacement of

actuator 110, but flexible enough to decouple, for example, parasitic X-Y movement of Z tube 124 (see Figure 1D) from flexure 132. Flexible element 134 may be on the order of 3 mm long and 0.2 mm in diameter, for instance. Sample 106 and more particularly sample holder 122 is coupled to link 156 of flexure 132. As a result, sample 106 mounted within SPM 100 moves substantially only in the intended direction in response to activation of actuator 110 (in this case, Z), thus causing "Z" movement of sample relative to reference structure 114. On the other hand, because, in the preferred embodiment, reference structure 114 is coupled to X-Y tube 126, reference structure 114 moves in conjunction therewith, thus transmitting this intended X-Y motion to flexure 132. As a result, sample 106 can move in the X and Y directions freely upon activation of X-Y tube section 126.

With more specific reference to Figures 2-4, a second source 164 of electro-magnetic radiation (e.g., a laser) which is part of an optical measuring device 163 is used in an apparatus to measure Z-movement of section 124. Source 164 is mounted so as to direct a beam of light "L" generally vertically (i.e., orthogonal to the sample surface) through focusing lens 166 and on to a mirror 168 of optical measuring device 163. Mirror 168 directs the beam towards the multi-bar linkage, also referred to as flexure 132 which, again, is mounted on reference structure 114, and which supports sample 106. A reflecting surface, such as a mirror 170 is mounted on one of the links 152 of flexure 132 and directs the beam towards the second mirror 172 in a corner-cube arrangement such that flexure 132 comprises part of optical measuring device 163 on another of the links of flexure 132 which thereafter directs the beam towards yet another reflecting surface 174. Reflecting surface 174 (e.g., a mirror) then directs the reflected beam towards a detector 178 to measure the movement of the sample in the vertical, or Z, direction. Again, because the flexible bar only transmits forces in the vertical direction, parasitic movement of the Z section 124 of actuator 110 is not transmitted to flexure 132 and thus such movement does not affect movement measured by the optical measuring device 163. Preferably, a cylindrical lens 176 is disposed intermediate mirror 174 and detector 178 (or it can be located at any point between laser 119 and detector 178 as desired) to maintain sufficient signal and thus enhance precision.

To monitor, for example, topographical changes on the surface of sample 106, appropriate feedback depending on the mode of AFM operation is provided. This is preferably implemented via an optical beam-bounce technique, as described previously. Electromagnetic radiation source 119 generates light (e.g., laser light) that is directed onto the back of cantilever 118, or a mirror attached thereto to direct the radiation toward detector 121. Detector 121 generates an appropriate signal that is provided to a feedback loop that generates a control signal that is used to manipulate tip-sample separation. In this arrangement, the control signals are indicative of sample characteristics.

Optical Sensing Of Actuator Movement And XY Plane

The actuator assembly including another optical measuring apparatus 190 for measuring lateral, or X-Y, movement of the sample coupled to actuator 110 is shown in more detail in Figures 5 and 6. Again, actuator assembly includes actuator 110 (preferably a piezoelectric tube) and a reference assembly 180 which comprises a reference structure 182, a coupling mount 135, flexible bar coupling 134, flexure 132, and sample holder 122, as described in detail below.

Again, in the preferred embodiment of the present invention, actuator 110 is formed of two sections; first, a lower section 126 is configured to deflect laterally in a plane perpendicular to the central axis of actuator 110 under program control. For this reason, as noted earlier, this section is known as the X-Y tube. Actuator 110 also includes an upper Z tube actuator 124 that is adapted to extend or contract in a direction substantially parallel to the longitudinal axis of actuator 110 under program control. Note that a discussion of an apparatus for controlling such actuators can be found, for example, in U.S. Patent No. 6,008,489, and other related applications.

The two tube sections 124, 126 of piezoelectric actuator 110 are coupled together end-to-end proximate to a circular collar 128 that extends around and is affixed to the actuator sections. Actuator assembly 110 is preferably coupled to frame 102 at its lower end,

for example, using collar mount 116 shown in Figures 5 and 6. In this embodiment, elongate reference structure 182 of reference assembly 180 extends around at least the Z tube 124 of actuator 110, and is fixed to the collar 128. Collar 128, in turn, is fixed to actuator 110 at or near the junction of the upper and lower actuator sections 124, 126. When X-Y tube is driven under program control, it deflects in a direction generally perpendicular to the longitudinal axis of actuator 110. Because collar 128, and reference structure 182 are fixed to the actuator near the top of the X-Y tube, they also deflect laterally. Again, the X-Y tube is preferably placed furthest from the structure it is translating (in this case sample holder 122 and sample 106) so as to maximize X-Y range of motion (i.e., scanning).

On the other hand, when Z tube 124 is driven under program control, it does not expand or retract collar 128, the fixed end of Z-tube coupled thereto. Therefore, the reference structure does not expand or retract since it is coupled to collar 128. In other words, when Z tube 124 extends or retracts, it extends or retracts relative to structure 182 which causes a substantial change in the relative position of the two at the upper (or free) end of Z tube 124, as highlighted previously.

In the operation of this embodiment, an optical measuring apparatus 190 measures movement of sample 106 in the X and/or Y directions (e.g., the XY plane) in response to voltage signals applied to X-Y actuator 126. Optical measuring apparatus 190 includes a light source 192, an objective 194 fixed to reference structure 182, and a position sensor 196. Movement of objective 194 depends on movement of reference structure 182, while light source 192 and position sensor 196 are stationary. Objective 194 is preferably located between light source 192 and position sensor 196.

Flexure 132 and reference structure 182 provide a rigid mechanical connection in the XY plane between sample 106 and X-Y actuator 126, therefore minimizing any X-Y error (parasitic X-Y motion, etc.) introduced by Z tube 124 in the XY plane. Movement of reference structure 182 is thus indicative of accurate movement of sample 106 in the XY plane in response to voltage signals applied to X-Y actuator 126. Likewise, movement of

objective 194 mounted to reference structure 182 corresponds to movement of sample 106 in the XY plane.

With objective 194, optical measuring apparatus 190 provides optical magnification between light source 192 and position sensor 196. In operation, X-Y actuator 126 is actuated in response to voltage signals and moves in a particular direction (e.g., in the X and/or Y directions), thereby causing reference structure 182 and corresponding objective 194 to move. Measuring the position at which a beam of electromagnetic radiation from light source 192 contacts position sensor 196 through objective 194 provides an indication of the movement of sample 106 as position sensor 196 and light source 192 are both fixed. In particular, the magnification provided by objective 194 is based on:

$$M = 1 + i/o \qquad \textit{Eqn. 1}$$

where "i" is the orthogonal distance from objective 194 to position sensor 196, and "o" is the orthogonal distance from objective 194 to light source 192. Objective 194 provides optical magnification to increase the signal-to-noise ratio by multiplying the signal by a factor of M (e.g., if $M = 5$, for every micron that objective 194 moves in the X and/or Y directions, the light beam moves across position sensor 196 by five microns, thereby increasing the signal-to-noise ratio by a factor of 5).

Objective 194 further comprises a set of separate microlenses (e.g., four) that is fixed to an outside surface 198 of reference structure 182 opposite an inside surface 200 adjacent to actuator assembly 110. Objective 194 does not focus the light beam to a point, but rather defocuses by integrating the light beam over a particular area. If, on the other hand, objective 194 focused the light beam to a point, surface asperities would become magnified, thereby introducing large distortions.

Position sensor 196 is an XY position sensor (e.g., a lateral effect photodiode) configured to detect the direction of the light beam and generate a displacement signal

indicative of movement of sample 106 in response to voltage signals applied to X-Y actuator 126 (e.g., in a direction generally perpendicular to the longitudinal axis of actuator 126).

AFM operation is as described previously. Again, to determine the height of various features at different locations on the sample surface, sample 106 is scanned so as to interact with stylus 120 in a regular raster pattern in XY, while sample 106 is also moved in Z by Z actuator 124. In operation, to direct sample 106 laterally, an electrical signal is applied to X-Y tube 126, which in turn causes an upper portion 202 of actuator assembly 110 to deflect in relation to stylus 120. Depending upon the signals applied to X-Y tube 126, this can cause sample 106 to move in two orthogonal directions relative to stylus 120.

Although the best mode contemplated by the inventors of carrying out the present invention is disclosed above, practice of the present invention is not limited thereto. It will be manifest that various additions, modifications and rearrangements of the features of the present invention may be made without deviating from the spirit and scope of the underlying inventive concept. For example, instead of coupling objective 194 to reference structure 182, either light source 192 or position sensor 196 could be fixed to reference structure 182. Note also that "couple," "coupling," etc. are used throughout to indicate a connection between two structures but that the connection does not necessarily have to be direct, it can be via another structure. The scope of still other changes to the described embodiments that fall within the present invention but that are not specifically discussed above will become apparent from the appended claims.